

Finally, to obtain even finer delay tuning, electrodes 44 can be attached across each crystal slab to apply an electrical field 94 and change the refractive index of the crystal via the electro-optic (or Pockel's) effect of the birefringent crystals, as shown in FIG. 9 and FIG. 10C. The two electrodes on each face of crystal slab 92 can be separated by an insulation layer 98.

In summary, the index switched photonic variable delay device has the properties of high packing density, low loss, easy fabrication, and virtually infinite bandwidth. The device is inherently two dimensional and has a packing density exceeding 25 lines/cm². The delay resolution of the device can be much less than a femtosecond (one micron in space) and its total delay exceeds 1 nanosecond. The delay accuracy achievable is high, and is only limited by the length accuracy of each crystal segment. The device can also be digitally programmed with low switching power (microwatts per switch or per bit). Such a device is ideal for a beam forming network of a phased array operating at Ka band (~40 GHz) and above frequencies and for millimeter wave transversal filters. In addition, the delay is reversible so that the same delay device can be used for both antenna transmitting and receiving. Finally, this index-switched variable delay device can be cascaded with a ladder-structured variable device to form a new device which combines the advantages of the two individual devices.

Although the description above contains many specificities, these should not be construed as limiting the scope of the invention but as merely providing illustrations of some of the presently preferred embodiments of this invention. Thus, the scope of the invention should be determined by the appended claims and their legal equivalents, rather than by the examples given.

What is claimed is:

1. An index-switched optical variable delay device for varying a path length of an optical beam, comprising:

A slab of birefringent crystal having a first birefringent axis and a second birefringent axis, a first array of corner reflectors being placed at a first side of said slab, a second array of corner reflectors being placed at an opposite side of said slab, and a multiple of polarization rotators each independently operable to rotate a first polarization state of an input light beam to a second polarization state which is substantially orthogonal to the first polarization state when being activated and leave the first polarization state unaffected when being de-activated; said two corner reflector arrays being such arranged that the optical beam entering from the first side of the slab towards the opposite side is reflected back by a first corner reflector on the opposite side towards a second corner reflector at the first side; the beam being reflected again by the second corner reflector towards a third corner reflector on the opposite side, and continuing being reflected back and forth across the slab by successive corner reflectors until exiting; the polarization rotators each being placed between the slab and a selected corner reflector.

2. The index-switched optical variable delay device of claim 1 further comprising multiple lenses each having a focal length being placed at a selected position to allow said optical beam to pass through each lens; a distance between two successive lenses being substantially twice said focal length.

3. The index-switched optical variable delay device of claim 1 wherein more than one such device being stacked together to form a multiple channel delay device.

4. The index-switched optical variable delay device of claim 3 wherein a pair of electrodes being placed across each slab so that an electric field can be applied to the slab.

5. A method of changing an optical path length of an optical beam comprising the steps of:

placing in a path of said optical beam a first polarization rotator operable to rotate a first polarization state of said optical beam to a second polarization state which is substantially orthogonal to the first polarization state when being activated and leave the first polarization state unaffected when being de-activated,

after said first polarization rotator, placing a first birefringent crystal segment having a first birefringent axis and a second birefringent axis;

making said optical beam propagate in said first birefringent crystal segment substantially perpendicularly to said first and second birefringent axes,

de-activating said polarization rotator so that said optical beam experiences a first refractive index,

activating said polarization rotator to rotate said first polarization state to said second polarization state to make said optical beam experience a second refractive index,

connecting multiple birefringent crystal segments with one another, with a polarization rotator sandwiched between any two adjacent crystal segments;

activating and de-activating each polarization rotator independently to make said optical beam experience different refractive indices in each birefringent crystal segment, thereby varying the path length of said optical beam passing through all said birefringent crystal segments.

6. The method of claim 5 wherein a polarization rotator array having multiple polarization rotators is placed in front of each said birefringent crystal segment to accept multiple optical beams.

7. An optical delay device to vary a path length of an optical beam, said delay device comprising:

a first polarization rotator configured to rotate the optical beam to a first polarization state when active and a second polarization state when inactive; and

a first birefringent crystal segment having a first end coupled with the first polarization rotator, said first birefringent crystal segment including a first birefringent axis substantially aligned with the first polarization state and a second birefringent axis substantially aligned with the second polarization state.

8. The optical delay device of claim 7 further comprising a second polarization rotator coupled with a second end of said first birefringent crystal segment.

9. The optical delay device of claim 8 further comprising a second birefringent crystal segment having an input end coupled to the second polarization rotator, a first birefringent axis of the second birefringent crystal segment substantially aligned with the first polarization state and a second birefringent axis of the second birefringent crystal segment substantially aligned with the second polarization state.

10. The optical delay device of claim 9 further comprising a plurality of polarization rotators and a plurality of birefringent crystal segments coupled with one another in an alternating order.

11. The optical delay device of claim 10 wherein the optical path difference between said first polarization state and said second polarization state in different birefringent crystal segments differs by a factor of two.

12. The optical delay device of claim 10 wherein different birefringent crystal segments having different birefringences.

13. The optical delay device of claim 9 further comprising a first polarization beamsplitter coupled with the first birefringent crystal segment;

- a first external polarization rotator placed between the first polarization beamsplitter and the first birefringent crystal segment;
- a second polarization beamsplitter coupled with an output end of the second birefringent crystal segment; and
- a second external polarization rotator placed between the second polarization beamsplitter and the second birefringent crystal.

14. The optical delay device of claim 7 wherein said first polarization rotator is fabricated with a material selected from the group consisting of liquid crystals, birefringent crystals, magneto-optic materials, and electro-optic crystals.

15. A multi-channel optical device to independently control path lengths for a plurality of optical beams, the multi-channel optical device comprising:

- a first polarization rotator array having at least two polarization rotation elements, each polarization rotation element configured to rotate a corresponding optical beam in the plurality of optical beams to a first polarization state when active and to rotate the corresponding optical beam to a second polarization state when inactive; and
- a first birefringent crystal segment having a first end coupled with the first polarization rotator array, said first birefringent crystal segment including a first birefringent axis substantially aligned with the first polarization state and a second birefringent axis substantially aligned with the second polarization state.

16. The multi-channel optical delay device of claim 15 further comprising a second polarization rotator array coupled with a second end of said first birefringent crystal segment.

17. The multi-channel optical device of claim 16 further comprising a second birefringent crystal segment having an input end coupled to the second polarization rotator array, said second birefringent crystal segment including a first birefringent axis of the second birefringent crystal segment substantially aligned with the first polarization state and a second birefringent axis of the second birefringent crystal segment substantially aligned with the second polarization state.

18. The multi-channel optical device of claim 17 further comprising a plurality of polarization rotator arrays and a plurality of birefringent crystal segments coupled with one another in an alternating order.

19. The multi-channel optical device of claim 18 wherein an optical path difference between said first polarization state and said second polarization state in different birefringent crystal segments increases by a factor of two.

20. The multi-channel optical device of claim 18 wherein different birefringent crystal segments having different birefringences.

21. The multi-channel optical device of claim 17 further comprising:

- a photodetector array having multiple photodetectors each operable to convert an optical signal to an electrical signal;
- an electrical signal combiner having multiple input ports and operable to combine the electrical signals from the multiple photodetectors;
- said photodetector array being coupled to an output end of the second birefringent crystal segment with each photodetector receiving an optical signal from each channel;
- said electrical signal combiner with each input port being coupled to a corresponding photodetector on the photodetector array.

22. The multi-channel optical delay device of claim 17 further comprising:

- a first polarization beamsplitter coupled with an input end of the optical delay device;
- a first external polarization rotator array placed between the first polarization beamsplitter and the input end of the optical delay device;
- a second polarization beamsplitter coupled with an output end of the second birefringent crystal segment; and
- a second external polarization rotator array placed between the second polarization beamsplitter and the second birefringent crystal segment.

23. The multi-channel optical device of claim 15 further comprising:

- A pair of electrodes being placed across said first birefringent crystal segment for applying a voltage in a predetermined direction.

24. The multi-channel optical device of claim 15 wherein an output end of the device being connected to an input end of a different multi-channel variable delay device, with each channel of the device aligned with each channel of the different device to form a cascaded multi-channel variable delay device.

25. A method of changing an optical path length of an optical beam comprising the steps of:

- receiving the optical beam in a first polarization rotator;
- adjusting the first polarization rotator to polarize the optical beam to a first desired polarization, and transmitting the output of said first polarization rotator through a first segment of birefringent crystal having a first birefringent axis and a second birefringent axis;
- inputting the optical beam output by said first segment of birefringent crystal into a second polarization rotator;
- adjusting the second polarization rotator to polarize the optical beam to a second desired polarization, and transmitting the output of said second polarization rotator through a second segment of birefringent crystal having a first birefringent axis and a second birefringent axis.

26. The method of claim 25 wherein said first and second polarization rotators are selected from the group consisting of liquid crystal polarization rotator, half-wave plate polarization rotator, magneto-optic polarization rotator, and electro-optic crystal based polarization rotator.

27. The method of claim 25 further comprising the steps of:

- determining the desired optical path length;
- applying a first activation signal to set the first polarization rotator and a second activation signal to set the second polarization rotator; said first and second activation signals determined by desired optical path lengths calculated in the determining step.

28. The method of claim 25 wherein one of the first desired polarization and the second desired polarization is aligned with one of the first and the second birefringent axes.

29. The method of claim 25 wherein each of the first polarization rotator and the second polarization rotator has at least two independent polarization rotating elements to accept at least two optical beams.

30. An optical delay device for varying a path length of an optical beam comprising:

- a birefringent crystal including a first birefringent axis and a second birefringent axis;
- a first corner reflector coupled to a first side of the birefringent crystal at a first position;

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a polarization rotator coupled to the birefringent crystal and positioned to receive the optical beam from the first corner reflector, the polarization rotator configured to switch the polarization of the optical beam between a first polarization state and a second polarization state;

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a second corner reflector positioned to reflect the optical beam output by the polarization rotator back into said birefringent crystal.

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